REMARKS

The Applicant thanks the Examiner for the thorough consideration given the present application. Claims 1-20 are pending, of which claim 20 has been added. Claims 1, 16, and 18 are independent. The Examiner is respectfully requested to reconsider the rejections in view of the remarks set forth herein.

Examiner Interview

If, during further examination of the present application, any further discussion with the Applicant's Representative would advance the prosecution of the present application, the Examiner is encouraged to contact Carl T. Thomsen, at 703-208-4030 (direct line) at his convenience.

Restriction Requirement

The Examiner has made the initial Restriction Requirement final, and has withdrawn claims 8-14 from further consideration. Inasmuch as claims 8-14 depend directly or indirectly from independent claim 1, it is respectfully requested that the Examiner rejoin and allow claims 8-14 upon allowance of independent claim 1.

The Examiner has made another Restriction Requirement in the Office Action dated February 3, 2011(which is repeated in the Advisory Action dated April 20, 2011), and has withdrawn claims 16-19 from further consideration, asserting that they are directed to inventions other than that originally claimed. This latest Restriction Requirement is traversed.

Once again, the Applicants respectfully submit that a serious burden has not been placed on the Examiner to consider all of the claims in a single application. Nowhere has the Examiner demonstrated that claims 16-19 are classified differently than claims 1-7 and 15. Thus, the Examiner has not demonstrated that a serious burden has not been placed on the Examiner. The Examiner is respectfully requested to reconsider his restriction and act on all of the claims in the present application. However, the Applicant respectfully submits that the combination of elements set forth in each of **independent claims 1, 16, and 18** are <u>not</u> different inventions.

Independent claim 1 recites "the micro-antenna has a flat meandering shape with plural turns extending in alternating directions," and **independent claim 16** recites "the micro-antenna has a flat undulating shape with plural turns." Both are illustrated in each of FIGS. 1(a) to 2(d) and 4 of the present application.

According to the *"Encarta World English Dictionary"* meandering and undulating are defined as follows:

Meandering:

1. **follow twisting route:** to follow an indirect route or course, especially one with a series of twists and turns

"The river meanders to the sea."

2. **wander slowly and aimlessly:** to move in a leisurely way, especially for pleasure or because of a lack of motivation

"meandering through the park"

http://www.bing.com/search?q=meandering&src=IE-SearchBox

Undulating:

1. *transitive and intransitive verb* **move sinuously like waves:** to move in waves or in a movement resembling waves, or cause something to move in this way

2. *intransitive verb* **go up and down gracefully:** to rise and fall gracefully in volume or pitch

http://www.bing.com/Dictionary/search?q=undulate&FORM=DTPDIA

Given the common meanings of meandering and undulating above, the Applicant respectfully submits that

"the micro-antenna has a flat meandering shape with plural turns extending in alternating directions," as set forth in **independent claim 1,** and "the micro-antenna has a flat undulating shape with plural turns," as set forth in **independent claim 16** are not patentably distinct inventions.

Further, the subject matter of **independent claim 18** was previously set forth in independent claim 1 and dependent claim 5 which depends from independent claim 1.

Further, the Examiner has not shown that a serious burden has not been placed on the Examiner to consider all of the claims in a single application. Once again, therefore, the Applicant submits that the Examiner's latest Restriction Requirement is not proper and should be withdrawn.

If the Examiner continues to insist that this latest Restriction Requirement is proper, he is respectfully requested to provide specific support to justify his restriction.

Declaration Under 37 CFR 1.132

It is gratefully appreciated that the Advisory Action dated April 20, 2011 states that the Declaration under 37 CFR §1.132 filed on April 14, 2011 overcomes each of the following rejections made in the Office Action dated February 3, 2011:

- Claims 1-3, 5-7, and 15 stand rejected under 35 U.S.C. §102(a) as being anticipated by Ichiki et al., Plasma Sources Science and Technology, Published September 2003; and
- Claim 4 stands rejected under 35 U.S.C. §103(a) as being unpatentable over Ichiki et al., Plasma Sources Science and Technology, Published September 2003.

Rejections Under 35 U.S.C. §103(a)

Claims 1-4 and 7 stand rejected under 35 U.S.C. §103(a) as being unpatentable over JP 2002-257785 in view of Yin et al., IEEE, 1999; and

claims 5 and 6 stand rejected under 35 U.S.C. §103(a) as being unpatentable over JP 2002-257785 in view of Yin et al., IEEE, 1999, and further in view of Mosheli (U.S. 2001/0047760).

These rejections are respectfully traversed.

<u>Arguments Regarding Independent Claims 1, 16, and 18 as Previously Presented</u>

Independent claim 1 as previously presented recites a combination of elements directed to a mocroplasma jet generator, including *inter alia*

"wherein the micro-antenna has a flat meandering shape with plural turns extending in alternating directions."

Independent claim 16 as previously presented recites a combination of elements directed to a mocroplasma jet generator, including *inter alia*

"wherein the micro-antenna has a flat undulating shape with plural turns."

Independent claim 18 as previously presented recites a combination of elements directed to a mocroplasma jet generator, including *inter alia*

"wherein the micro-antenna has a flat meandering shape with plural turns,

wherein the substrate is made of one selected from the group consisting of sapphire, aluminum nitride, silicon nitride, boron nitride, and silicon carbide."

The Applicant respectfully submits that the combination of elements as set forth in each of **independent claims 1, 16, and 18** is not disclosed or made obvious by any combination of the prior art of record, including **JP 2002-257785, Yin et al., IEEE, 1999,** and **Mosheli.**

The Examiner alleges that **JP 2002-257785** discloses a flat meandering shape with one turn. The Applicant respectfully disagrees.

As can be seen in the English translation of paragraph **[0016]** of **JP 2002-257785** below, this document merely discloses "one-roll monotonous type antenna (3) with an inside diameter of 2 mm ..."

> **[0016]** ... Then, invention of this application is taken as the inductive-coupling microplasma source part by VHF drive. For example, <u>drawing 1</u> is a partial composition photograph of the flat surface which showed the example. For example, it can be considered as the discharge tube capillary tube (2) whose width and depth are 1-5 mm, and copper plating and a microplasma chip with an one-roll monotonous type antenna (3) with an inside diameter of 2 mm produced

by photo lithography in the center of a chip (1) made from quartz of 30 mm squares.

Further, as can be seen in FIG. 1 of **JP 2002-257785**, antenna (3) has a U-shape with parallel sides having equal lengths.

The Applicant respectfully submits that the "one-roll monotonous type antenna (3) with an inside diameter of 2 mm," and having a U-shape with parallel sides having equal lengths as disclosed in **JP 2002-257785**, does not teach or suggest any of:

"a flat meandering shape with plural turns extending in alternating directions," as set forth in **independent claim 1**, or

"wherein the micro-antenna has a flat undulating shape with plural turns," as set forth in **independent claim 16,** or

"wherein the micro-antenna has a flat meandering shape with plural turns,

wherein the substrate is made of one selected from the group consisting of sapphire, aluminum nitride, silicon nitride, boron nitride, and silicon carbide," as set forth in **independent claim 18.**

As can be seen in **Yin et al. FIG. 2,** this document merely discloses helical and spiral coils. See, for example,

- The caption under FIG. 2, which states "FIG. 2 – Top and bottom view of a miniature ICP circuit fabricated on a copper clad epoxy board. A U.S. dime is (φ-18 mm) shown as a scale reference,"
- page 1516, II Experiment, A. which merely discloses "a 20-turn coil wound around a 6mm Pyrex tube, and
- pages 1517 to 1518, Experiment B and C, Table 1, and FIGS. 2 and 3 which merely disclose spiral coils.

It is clear from **Yin et al. FIGS. 2 and 3**, that the **Yin et al.** reference discloses a large-scale plasma generated by a device with a spiral cord antenna. The present invention as set forth in each of **independent claims 1, 16, and 18** does not belong to such ICPs which

produce broad plasma. Instead, the presently claimed invention is directed to a micro plasma jet generator for producing micro plasma in a micro-space.

Further, according to the *"Encarta World English Dictionary,"* spiral is defined as follows:

Spiral:

1. **continuous circling flat curve:** in mathematics, a flat curve or series of curves that constantly increase or decrease in size in circling around a central point.
   http://www.bing.com/search?q=spiral+encarta&src=IE-SearchBox

Further, the "*Oxford Advance Learner's Dictionary*," defines spiral as:

Spiral:

a continuous curved line that winds around a central point, with each curve further away from the centre."

Given the differences between the common meanings of "meandering and undulating," and the common meaning of "spiral," the Applicant respectfully submits that

Thus, no combination of **JP 2002-257785, Yin et al., IEEE, 1999,** and **Mosheli** (which merely disclose a U-shaped coil and spiral coils) cannot be combined to teach of suggest:

"wherein the micro-antenna has a flat meandering shape with plural turns extending in alternating directions" (as in **independent claim 1**),

"wherein the micro-antenna has a flat undulating shape with plural turns" (as in **independent claim 16**), or

"wherein the micro-antenna has a flat meandering shape with plural turns,

wherein the micro-antenna has a flat meandering shape with plural turns, wherein the substrate is made of one selected from the group consisting of sapphire, aluminum nitride, silicon nitride, boron nitride, and silicon carbide" (as in **independent claim 18**).

As the Examiner knows well, a *prima facie* case of obviousness must be established in order for a rejection under 35 U.S.C. 103(a) to be proper.

M.P.E.P. section 2143 sets forth examples of basic requirements of a *prima facie* case of obviousness:

> "The Supreme Court in *KSR International Co. v. Teleflex Inc.*, 550 U.S. ___, ___, 82 USPQ2d 1385, 1395-97 (2007) identified a number of rationales to support a conclusion of obviousness which are consistent with the proper "functional approach" to the determination of obviousness as laid down in *Graham*. The key to supporting any rejection under 35 U.S.C. **103** is the clear articulation of the reason(s) why the claimed invention would have been obvious. The Supreme Court in *KSR* noted that the analysis supporting a rejection under 35 U.S.C. **103** should be made explicit."

One of the exemplary rationales that may support a conclusion of obviousness in accordance with the KSR decision is set forth in M.P.E.P. 2143 (C). This exemplary rational relates to "use of known technique to improve similar devices (methods, or products) in the same way."

Referring to M.P.E.P. 21433 (C), the following is stated:

> <u>"To reject a claim based on this rationale, Office personnel must resolve the *Graham* factual inquiries. Then, Office personnel must articulate the following:</u>
>
> **(1)** a finding that the prior art contained a "base" device (method, or product) upon which the claimed invention can be seen as an "improvement;"
>
> **(2)** a finding that the prior art contained a "comparable" device (method, or product that is not the same as the base device) that has been improved in the same way as the claimed invention;
>
> **(3)** a finding that one of ordinary skill in the art could have applied the known "improvement" technique in the same way to the "base" device (method, or product) and the results would have been predictable to one of ordinary skill in the art; and

(4) whatever additional findings based on the *Graham* factual inquiries may be necessary, in view of the facts of the case under consideration, to explain a conclusion of obviousness.

The rationale to support a conclusion that the claim would have been obvious is that a method of enhancing a particular class of devices (methods, or products) has been made part of the ordinary capabilities of one skilled in the art based upon the teaching of such improvement in other situations. One of ordinary skill in the art would have been capable of applying this known method of enhancement to a "base" device (method, or product) in the prior art and the results would have been predictable to one of ordinary skill in the art. The Supreme Court in *KSR* noted that if the actual application of the technique would have been beyond the skill of one of ordinary skill in the art, then using the technique would not have been obvious. *KSR*, 550 U.S. at ___, 82 USPQ2d at 1396. <u>If any of these findings cannot be made, then this rationale cannot be used to support a conclusion that the claim would have been obvious to one of ordinary skill in the art</u>." *(emphasis added)*

Regarding **item (1)** above, the Examiner appears to consider **JP 2002-257785** as representing the prior art containing a "base" device upon which the claimed invention can be seen as an "improvement."

As discussed, **JP 2002-257785** merely discloses an antenna (3) having a <u>single turn</u> to form a U-shape with parallel sides having equal lengths.

Regarding **item (2)** above, the Examiner appears to consider **Yin et al.** as representing the prior art containing a "comparable" device that has been improved in the same way as the claimed invention.

However, the **Yin et al.** reference merely discloses spiral and helical antennas.

The Applicant respectfully submits that the Examiner has failed to articulate at least **items (1) and (2)** above as is required.

Certainly, the Examiner cannot reasonably argue that a "spiral shape" of **Yin et al.** is "comparable" to either a "meandering shape with plural turns in alternating directions," or an "undulating shape."

The "spiral shaped" and "helical shaped" antenna of **Yin et al.** has a shape that merely turns continuously in one direction. A spiral or a helix cannot possibly be formed with plural turns in alternating directions.

JP 2002-257785 merely discloses a single turn.

Therefore, no combination of

- Yin et al. (which discloses a "spiral shaped" and "helical shaped" antenna which turns continuously in a single direction), and
- JP 2002-257785 (which merely discloses a single turn),

can teach, suggest, or make obvious:

"a flat meandering shape with plural turns extending in alternating directions," as set forth in **independent claim 1**, or

"wherein the micro-antenna has a flat undulating shape with plural turns," as set forth in **independent claim 16,** or

"wherein the micro-antenna has a flat meandering shape with plural turns,

wherein the micro-antenna has a flat meandering shape with plural turns, wherein the substrate is made of one selected from the group consisting of sapphire, aluminum nitride, silicon nitride, boron nitride, and silicon carbide" (as in **independent claim 18**).

In view of the above, the Applicant respectfully submits that the Examiner has failed to establish a *prima facie* case of obviousness.

In the last two lines of the Advisory Action (section (ii)), the Examiner states:

> "Furthermore, Yin also indicates that such configuration (the spiral in FIG. 2 of **Yin et al.**) generates uniform and stable plasma and improves efficiency (page 1517 &1519, FIG. 4). Therefore, it would be obvious for one skilled in the art to utilize a planar spiral coil with plural turns."

However, the Examiner has provided no evidence regarding how or if one skilled in the art would find either "a flat meandering shape with plural turns extending in alternating directions," as set forth in **independent claim 1**, or "wherein the micro-antenna has a flat undulating shape with plural turns," as set forth in **independent claim 16,** or "wherein the micro-antenna has a flat meandering shape with plural turns," (as in **independent claim 18**) would be obvious based on the spiral and helical antenna of Yin et al.

Yin et al. Teaches Away from the Inventions Set Forth in Independent Claims 1, 16 and 18

The spiral or helical shaped antenna of Yin et al. is formed with a single continuous curve always turning in the same direction. On the other hand, each of **independent claims 1 16, and 18** discloses an antenna either a "flat meandering shape having plural turns" or a "flat undulating shape having plural turns." Further, **independent claim 1** sets forth a "flat meandering shape with plural turns extending in alternating directions."

The spiral or helical shaped antenna of the **Yin et al.** reference teaches away from and conflicts with each of the shapes set forth in each of **independent claims 1, 16, and 18.**

Copy of "Review of Inductively Coupled Plasmas for Plasma Processing," J. Hopwood, 1992

The Applicant has attached a copy of "Review of Inductively Coupled Plasmas for Plasma Processing," J. Hopwood, 1992 for the Examiner's consideration.

As the Examiner will recognize, J. Hopwood is a co-author of the **Yin et al.** reference cited by the Examiner. As is evident from the FIGS. 1(c) and 4 of the 1992 paper by J. Hopwood, it is clear that FIG. 2 of Yin et al. reference discussed above depicts a large area plasma generated by a device with a spiral cord antenna.

On the other hand, as discussed above, the present invention as set forth in each of **independent claims 1, 16, and 18** does not belong to ICPs which produce large area plasma. Instead, the presently claimed invention is directed to a micro plasma jet generator for producing micro plasma in a micro-space.

At least for the reasons explained above, the Applicant respectfully submits that the combination of elements as set forth in each of **independent claims 1, 16, and 18** is not disclosed or made obvious by any combination of the prior art of record, including **JP 2002-257785, Yin et al., IEEE, 1999,** and **Mosheli.**

Therefore, **independent claims 1, 16, and 18** are in condition for allowance.

If the Examiner continues to insist that the subject matter set forth in each of **independent claims 1, 16, and 18** is an obvious variation of the disclosure in the combination of **JP 2002-257785, Yin et al., IEEE, 1999,** and **Mosheli,** he is respectfully requested to provide specific evidence to support his conclusions. Without such evidence, the rejection of these claims should be withdrawn.

Dependent Claims

All dependent claims are in condition for allowance due to their dependency from allowable independent claims, or due to the additional novel features set forth therein.

For example, each of **dependent claims 15, 17, and 19** recites

"wherein the plural turns extend up and down or back and forth with respect to an edge of the substrate." See FIGS. 1(a) to 2(d) and 4 of the present application for support.

By contrast, the Yin et al. document merely discloses a micro-antenna formed with

> **a continuous circling flat curve:** in mathematics, a flat curve or series of curves that constantly increase or decrease in size in circling around a central point.

Therefore, **dependent claims 15, 17, and 19** should be allowable.

If the Examiner continues to insist that the subject matter set forth in each of **dependent claims 15, 17, and 19** is an obvious variation of the disclosure in the combination of **JP 2002-257785, Yin et al., IEEE, 1999,** and **Mosheli,** he is respectfully requested to provide specific evidence to support his conclusions. Without such evidence, the rejection of these claims should be withdrawn.

For anther example, added **dependent claim 20** recites

"wherein the flat meandering shape with plural turns extending in alternating directions of the micro-wave antenna includes at least two U-shaped portions formed continuously one after the other."

The "spiral" or "helix" of **Yin et al., IEEE, 1999** cannot be combined with the **"**single U-shape" of **JP 2002-257785** to arrive at **"**the flat meandering shape with plural turns extending in alternating directions of the micro-wave antenna includes at least two U-shaped portions formed continuously one after the other," as set forth in **dependent claim 20.**

If the Examiner insists that the subject matter set forth in each of **dependent claim 20** is an obvious variation of the disclosure in the combination of **JP 2002-257785, Yin et al., IEEE, 1999,** and **Mosheli,** he is respectfully requested to provide specific evidence to support his conclusions. Without such evidence, dependent claim 20 should be considered allowable.

All pending claims are now in condition for allowance.

Accordingly, reconsideration and withdrawal of the rejections under 35 U.S.C. §103(a) are respectfully requested.

CONCLUSION

All of the stated grounds of rejection have been properly traversed, accommodated, or rendered moot. It is believed that a full and complete response has been made to the outstanding Office Action, and that the present application is in condition for allowance.

If the Examiner believes, for any reason, that personal communication will expedite prosecution of this application, he is invited to telephone Carl T. Thomsen (Reg. No. 50,786) at (703) 208-4030 (direct line).

If necessary, the Commissioner is hereby authorized in this, concurrent, and future replies to charge payment or credit any overpayment to Deposit Account No. 02-2448 for any additional fees required under 37 C.F.R. §§1.16 or 1.17, particularly extension of time fees.

Respectfully submitted,

Date: May 3, 2011

By James M. Slattery

James M. Slattery
Reg. No. 28,380

BIRCH, STEWART, KOLASCH & BIRCH, LLP
8110 Gatehouse Road, Suite 100E
P. O. Box 747
Falls Church, VA 22040-0747
(703) 205-8000

JMS:CTT:jam

Plasma Sources Sci. Technol. 1 (1992) 109–116. Printed in the UK

Review of inductively coupled plasmas for plasma processing

J Hopwood

IBM Research Division, T J Watson Research Center, Yorktown Heights, New York 10598, USA

Received 7 March 1992, in final form 1 April 1992

Abstract. The need for large-area, high-density plasma sources for plasma-aided manufacturing of integrated circuits has created a renewed interest in inductively coupled plasmas (ICPs). In this paper several ICP reactor geometries are briefly reviewed. Typically, inductive coupling of RF power (0.5–28 MHz) can produce ion densities in excess of $10^{12}\,cm^{-3}$ even at sub-millitorr pressures. Existing electromagnetic field models of ICPs are examined and found to be in reasonable agreement with experimental results. Sputter deposition, anodic silicon oxidation and polymer etching using ICPs are also described. It is concluded that ICPs are promising candidates for meeting the future requirements of plasma processing, although considerable process development, plasma characterization and modelling are still needed.

1. Introduction

For over 100 years inductively coupled plasmas (ICPs) have been generated and studied. Recently the trend toward high-rate, single-wafer processing in integrated circuit (IC) fabrication has motivated the development of low-pressure (< 1 Torr) ICPs for plasma-aided materials processing applications. The requirements for modern processing plasmas include high densities of ions, electrons and radicals, excellent uniformity over diameters of at least 20 cm, low and controllable ion energies and negligible contamination from reactor sputtering or particulate generation. A review of inductively coupled plasmas reveals that most of these requirements can already be met using a readily available RF (13.56 MHz) heating frequency and relatively simple source designs.

It is naturally desirable to understand the physics of the ICP as an aid to controlling the plasma process. Since low-pressure ICP implementations for IC processing plasmas are relatively new, these sources have not been investigated as extensively as other high-density plasmas such as electron cyclotron resonance (ECR) plasmas [1] and helicon wave plasmas [2, 3]. For an overview of high-density plasma sources the reader is referred to [4]. This paper contains a brief review of the current understanding of the properties of ICPs with an emphasis on low-pressure, plasma-processing applications.

2. Review of inductively coupled plasma technology

As the name implies, the inductively coupled plasma uses an inductive circuit element adjacent to (or immersed inside) a discharge region in order to couple energy from an RF power source to an ionized gas. The inductive circuit element is typically a helical or spiral-like conductor. An additional electrical reactance is used to tune the inductor such that an electrical resonance at the RF driving frequency is obtained. Properly implemented, the resonant circuit causes large RF currents to flow in the inductive element. The RF magnetic flux generated by these currents then penetrates into the adjacent discharge region. Using Faraday's law, $\nabla \times \boldsymbol{E} = -\partial \boldsymbol{B}/\partial t$, one can see that the time-varying RF magnetic flux density ($\boldsymbol{B}$) induces a solenoidal RF electric field ($\boldsymbol{E}$). It is this 'inductive' electric field which then accelerates free electrons in the discharge and sustains the plasma.

Since the inductive coupling element is driven in an electrical resonance condition, one can expect high potentials to exist on the structure. Such RF potentials will lead to capacitive coupling to the discharge as one would observe in RF planar parallel-plate plasma reactors. Capacitively coupled plasmas are characterized by high voltages and observable sheaths. Ions are accelerated across the sheaths to the walls at high energy and can cause sputtering and heating of the walls. It is not uncommon to observe weak, capacitively coupled *E-discharges* in inductively coupled plasma sources at low absorbed powers [5–7]. As RF power is increased, a sudden increase in luminosity and density is observed at pressures above ~30 mTorr [6], signaling the onset of inductive coupling or the *H-discharge*. The mode of coupling (capacitive or inductive, E or H) has frequently been a matter of debate since the original inductive plasmas [7]. Some implementations of ICP reactors attempt to minimize the degree of capacitive coupling (and its negative side-effects) by placing split Faraday

shields between the inductive coupler and the discharge wall. Since high potentials exist on the inductive couplers, it is arguable that any ICP is *entirely* inductively coupled and, for the purpose of this review, high-density plasma sources which may be only partly inductively coupled will be considered as ICPs.

In what follows an attempt has been made to classify the various forms of inductively coupled plasma sources. Conspicuously absent from the listing below is the helicon wave source [2, 3] which is sometimes referred to as a resonant inductive plasma etcher [8, 9] (RIPE). In this source, however, the plasma is magnetized longitudinally by solenoidal electromagnets, and coupling is achieved by an RF transverse electromagnetic helicon wave. The divisions among non-magnetized ICPs reviewed here are made primarily along geometrical features and are:

(i) helical inductive couplers—cylindrical plasmas;
(ii) helical resonators—cylindrical plasmas;
(iii) spiral inductive couplers—planar plasmas;
(iv) immersed inductive couplers;
(v) transformer-coupled plasmas.

2.1. Helical inductive couplers

Historically, Hittorf is credited by Eckert [10] with producing the first plasma by induction using a coil surrounding a tube in 1884. These early inductive plasmas were often referred to as 'ring' discharges since the limited skin depth of the exciting field in the discharge caused the periphery to glow more brightly. More recently, high-pressure (~ 1 atm) induction plasmas or 'induction arcs' have been extensively studied and used. Eckert [11] gives a comprehensive review of high-pressure ICPs. Applications include spectral chemical analysis, plasma-assisted chemical synthesis, crystal growth and thermalization of gases to produce thrust from a plasma jet. At high pressures, however, the plasma is dominated by volume recombination rather than diffusion which results in a non-uniform, small-volume plasma. In addition, high-pressure arcs are characterized by high neutral gas temperatures (1000–10 000 K). These properties make the induction arc unsuitable for processing damage-sensitive, large-area wafers and dictate low-pressure operation.

The geometry of the helical-class ICP is shown in figure 1(*a*). The induced electric field within the plasma is azimuthal, forming closed loops about the axis, and the RF magnetic field is directed along the central axis of the discharge [5, 10, 12]. Several models [5, 11–13] have been published which describe the induction fields while taking into account such factors as finite conductivity and radial variation of plasma density. In general, the induction field is maximum at the plasma tube circumference and decreases monotonically toward the centre. The result at higher pressures can be a ring-shaped discharge as viewed along the axis. At low pressures, however, diffusion processes increase the plasma density near the centre, where the induction field is low, thus providing a more radially uniform discharge.

It is possible in the helical-class ICP for the high RF potential which forms end-to-end across the inductive coupler to produce an axial electric field through the discharge. The axial field will produce a weak capacitive discharge, particularly during low-power operation [5, 6]. A cylindrical conducting shield (Faraday shield) placed around the discharge chamber will short-out the axial electric field. Longitudinal slots must be cut from the shielding, however, so that the shield does not function as a short-circuited secondary transformer winding with the inductive coupler acting as the primary, thus inhibiting induction fields from the discharge region. When operated in the inductive mode, argon ion densities [6] in excess of $10^{12}\,\mathrm{cm}^{-3}$ have been reported at 64 mTorr.

The barrel etcher [14] is a traditional plasma processing tool which is very similar in appearance to figure 1(*a*). Plasma ion density in barrel reactors is typically only of the order of $10^{10}\,\mathrm{cm}^{-3}$ or less, suggesting that the coupling mechanism is capacitive. In addition, wafers are loaded into the centre of the cylindrical discharge vessel for processing where they would significantly disrupt the inductive fields. For this reason, plasma processing in helical inductive plasmas and helical resonators (discussed below) frequently occurs in a remote, downstream chamber which is separate from the plasma generation region.

2.2. Helical resonator

The helical resonator plasma source [15–18] also consists of a cylindrical discharge tube within a helical coil. The coil, however, is designed with an electrical length of $(\lambda/4 + n\lambda/2)$ or $(\lambda/2 + n\lambda/2)$, where $n = 0, 1, 2, \ldots$ and λ is the wavelength of the excitation frequency. The former design is a quarter-wave resonator and the latter is a half-wave resonator. As shown in figure 1(*b*) the coil is within a conducting enclosure which provides a parasitic capacitance from the coil to ground. In addition, a trimming capacitor is usually connected between the coil and ground to adjust the capacitance to ground such that the structure resonates. Typically one end of the coil is grounded and, in the quarter-wave resonator, the other end is floating. In the half-wave design, both ends of the coil are grounded. RF power is applied at a centre tap of the coil. The presence of the discharge chamber and plasma within the helical resonator will perturb the resonant frequency of the reactor. A treatment of this perturbation is given in [19].

Although there is currently some debate as to whether the helical resonator is truly an inductively coupled plasma, high-density plasmas can be generated using a split Faraday shield (described above) between the coil and the plasma. This shield will short-out capacitive fields and allow primarily inductive excitation of the discharge. In addition, ion densities of 10^{10}–$10^{12}\,\mathrm{cm}^{-3}$ have been reported in commercially available helical resonators [18] thus exceeding densities produced by capacitively coupled plasmas (typically $\sim 10^{10}\,\mathrm{cm}^{-3}$).

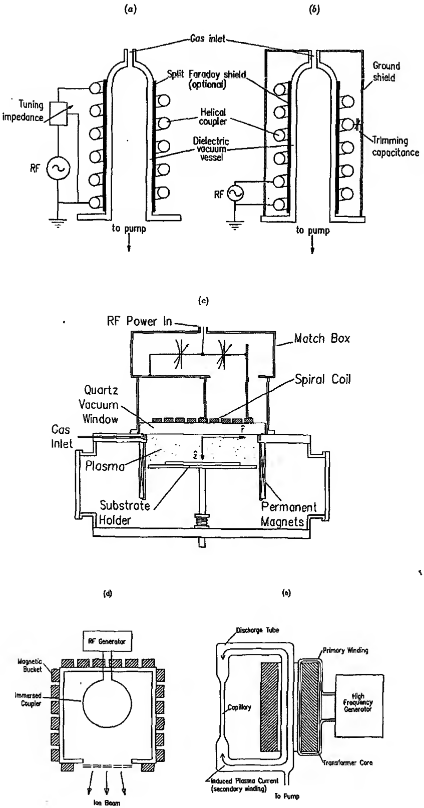

Figure 1. Cross-sectional schematic diagrams of various inductively coupled plasma reactors: (*a*) helical coupler, (*b*) helical resonator, (*c*) spiral coupler, (*d*) immersed coupler and (*e*) transformer-coupled plasmas. See text for details and references.

2.3. Spiral inductive couplers

In processing applications where it is desirable to generate uniform plasmas over large, planar areas or in ion sources where one wishes uniform ion generation over planar extraction grids, spiral-like inductive couplers which lie in (or nearly in) a plane have been developed [20–23]. A typical planar design is shown in figure 1(*c*) where a spiral-like coil (shown in cross section) is separated from the low-pressure discharge chamber by a dielectric (typically quartz) vacuum window. A capacitance in series with the spiral inductor is tuned such that the driving circuit resonates at the RF frequency. These reactors sometimes use permanent-magnet multipolar buckets in the discharge chamber to confine the plasma, improve uniformity and increase the discharge density. The effects of capacitive coupling between the coil and the plasma are reduced by using a thick-cross-section dielectric window.

The geometry of the spiral ICP holds particular advantages in processing of planar surfaces such as wafers. Since the skin depth of a 13.56 MHz RF induction field is approximately 1–2 cm in plasmas with electron densities of the order of $10^{11}\,cm^{-3}$, the substrate may be placed in close proximity to the inductive coil. Typically, the coil is separated from the plasma by a 1–3 cm quartz window and the substrate is positioned 5–10 cm below the window (2.5–10 skin depths). The induction electric field decays exponentially within the plasma such that the field strength is attenuated by a factor of at least 12 (i.e. exp 2.5) at the substrate. By processing in close proximity to the region of plasma generation, plasma losses such as electron–ion and neutral–neutral recombination are reduced as compared to remote, downstream processing. This results in improved ion generation efficiencies as measured *at the substrate*. For the source in figure 1(*c*), argon-ion generation efficiency measured at the substrate varies from 150–300 eV/ion for argon densities of $(1–4)\times 10^{11}\,cm^{-3}$ at 5 mTorr and 100–1000 W RF power. Although it can be argued that RF power is inexpensive relative to the other costs of IC fabrication, reduced power absorption may provide other benefits. In downstream source configurations, for example, the plasma in the generation region may typically be an order of magnitude more dense than at the substrate [24]. Such an excessively dense plasma in the source region may increase sputter contamination, UV damage and neutral gas heating at the substrate. Although the principle is not proved, it is at least intuitively appealing to produce a plasma of exactly the proper density, and no more, at the point of use. Examples of the performance and modelling of planar, spiral ICPs which approach this ideal are given later in the paper.

2.4. Immersed inductive couplers

In the ICPs discussed so far, the inductive coupling element has been physically outside the discharge region. In the immersed-coil class, the inductor is positioned within the plasma vessel (figure 1(*d*)). This design has a distinct advantage in metal sputtering [25] applications. Metal deposition on the dielectric plasma-vessel walls of non-immersed ICPs eventually suppresses plasma generation by acting as a single-turn, short-circuited secondary winding which is closely coupled to the inductive driver. Although Yamashita [25] reports no measurable impurities in the metal films deposited by immersed ICP sputter deposition, contamination sputtered from an immersed inductive element is a concern in other processing applications such as etching and deposition. Immersed coils have successfully been used in ion beam sources [26–28] where a loop antenna is located within a magnetic bucket vacuum vessel (see figure 1(*d*)). To prevent sputter erosion of the antenna, glass cloth is fused to the metal inductor. Helium-ion densities of $2\times10^{11}–5\times10^{12}\,cm^{-3}$ at 0.5–5 mTorr have been reported in pulsed RF (3-100 kW, 1 MHz) immersed ICP ion sources [26].

2.5. Transformer-coupled plasmas

ICPs have also been used in laser design [29–31] where a ferrite core transformer couples low- or high-frequency (2.5 kHz–1 MHz) energy to a ring-shaped plasma chamber (see figure 1(*e*)). Here the reader may observe that the plasma functions as a single-turn secondary winding around the closed path of the vacuum vessel. The induction electric field resides along the axis of the tube, rather than in the azimuthal loops of the helical and spiral ICPs. Reference [30] describes an ICP with a similar closed-loop plasma tube, but a single-turn, air-core primary winding is used. This implementation has been operated from 3.5–28 MHz. The plasma in these configurations is most intense in the narrow *capillary* region which is typically 1–3 mm in diameter. For laser operation an optical cavity is positioned to include the capillary volume. While the narrow cylindrical geometry described here is not appropriate for large planar areas encountered in semiconductor fabrication, it may prove useful for continuous-strand processing systems and other applications.

3. Modelling of ICPs

The simplest model of the ICP is a discrete circuit element model known as the transformer model [5] shown in figure 2. In this model the inductive coupling structure is described as an N-turn primary transformer winding with self-inductance, L_p. The high-density plasma is modelled as a single-turn secondary winding and a series-connected plasma impedance, Z_{plasma}. The coupling coefficient, K, between the primary and secondary windings may approach unity for helical, immersed and transformer-coupled reactors. For spiral-like inductive couplers, K may be somewhat less than one [20]. This reduction in coupling coefficient is due to the leakage magnetic flux from the primary which does not intersect the secondary defined by the plasma. The transformer

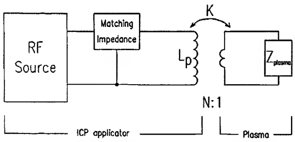

Figure 2. Schematic diagram of the transformer model of inductively coupled plasmas [5].

model is sufficient for relating external circuit parameters such as coil current and voltage to the 'plasma impedance', but does not directly describe the fields within the plasma or any plasma physics.

More sophisticated electromagnetic models have been developed to describe the induction fields within the discharge. Thomson [13], in one of the earliest theoretical treatments of the ICP, produced analytical expressions for the field required to sustain a plasma by induction. In his work, Thomson concludes that 'it does not require a very intense magnetic field to produce he discharge'. In the same work, Thomson also identified the tendency of currents induced near the periphery of the discharge to shield the central regions from induction currents. Recent measurements [32] in spiral-like ICPs (see figure 1(*c*)) are shown in figure 3. Notice that the 13.56 MHz magnetic flux density is quite low at only a few gauss. The corresponding induced electric field is of the order of only 4–8 V cm^{-1}. Figure 3 also demonstrates the shielding of the inductive fields by plasma currents. Induction electric fields which are parallel to a planar plasma surface are expected to decay spatially with an exponential dependence and a decay constant given by

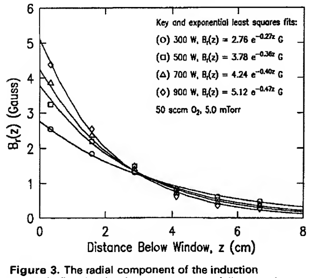

Figure 3. The radial component of the induction magnetic flux density decreases exponentially away from the spiral-shaped coupler.

$\delta \simeq c/\omega_{pe}$, where c is the speed of light in a vacuum and ω_{pe} is the electron plasma frequency [33]. The full curves in figure 3 are exponential least-squares fits to the experimental data which confirm the theoretical shielding depth (or *skin depth*) of the induction field.

The Thomson [13] model assumes uniform and real conductivity across the helical-type ICP discharge diameter. Eckert [10] refined this model by combining positive column diffusion theory with the electromagnetic model and the effects of finite collision frequency. Henriksen *et al* [12] offer a similar solution with the assumption of a parabolic radial electron density profile.

The preceding models of helical ICPs all make an *a priori* assumption that the magnetic field is axial and the electric field and current are entirely azimuthal. For the spiral-like, planar ICP (figure 1(*c*)) these simplifying assumptions are not easily justified. A schematic representation of the induction electric and magnetic fields for the spiral coil ICP is shown in figure 4. The reader may observe that the *B*-field is not directed entirely along the axis as in helical coil ICPs. The RF fields, however, can be numerically modelled by solving Maxwell's equations using finite element analysis (FEA). Solutions for the electric field are shown in figure 5 for such a planar ICP [32]. The electric field in a plane 2.5 cm below the vacuum window is shown by arrows where the relative size of the arrow is proportional to the strength of the field. The square-spiral coil is shown in outline to assist the reader. This model is a three-dimensional numerical solution to Maxwell's equations assuming a cold, collisionless and uniform plasma with a relative permittivity given by $\varepsilon_r = 1 - (\omega_{pe}/\omega)^2$ where ω_{pe} is the electron plasma frequency and ω is the RF frequency. Direct measurement of the magnetic flux by a small loop antenna, movable within the plasma, has experimentally confirmed the accuracy of this model. It is interesting to note that the electric field is in fact dominantly azimuthal within the bulk of this high-electron-density plasma. One would expect that axial electric fields due to capacitive coupling from the coil to the plasma would quickly decay over the distance of several Debye lengths [33] (which is of the order of 100 μm). Nonetheless, such capacitive fields may play an important role in the plasma interactions at the window such as sputtering.

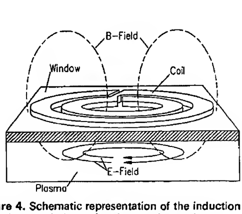

Figure 4. Schematic representation of the induction fields for a planar, spiral coupler above a dense plasma.

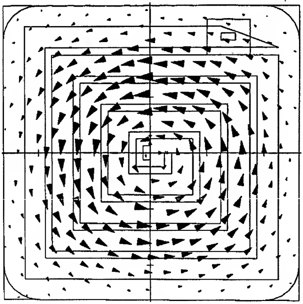

Figure 5. Induction electric field vectors from a three-dimensional numerical solution to Maxwell's equations are shown in a plane parallel to the inductive element 2.54 cm within the plasma. The outline of the square, spiral coupler is superimposed over the field plot.

The results of modelling of spiral-coupled ICPs indicate that scaling the diameter of the plasma may be accomplished by simply increasing the diameter of the coil. The larger plasma volume will necessarily require an increase in RF power to maintain the power density within the discharge. The subtle but practical problem of parasitic capacitance arises during scale-up, however, if the self-inductance of the coil increases as the diameter is enlarged (e.g. by adding more turns to the coil). In order to produce the large RF currents required for inductive coupling, the coil is tuned by an external capacitance to resonate at the RF frequency. For a typical 25 cm coil the inductance is $\sim 2\,\mu$H. The corresponding series capacitance required to achieve resonance at 13.56 MHz is ~ 70 pF according to $\omega^2 = 1/LC$. As the inductance of the coupler increases, the series capacitance must decrease to maintain the resonance condition. Eventually the scaled-up inductance will reduce the series capacitance to the order of 10 pF. Under these conditions parasitic capacitances between ground and the coupling circuit, which are also of the order of 10 pF, will inhibit tuning of the coil. Care must be taken in the engineering of the large ICPs to minimize parasitic capacitances and the self-inductance of the coupler. Somewhat lower frequency operation will also alleviate the potential problem of parasitic capacitance in large ICPs. Practically speaking, however, manufacturing environments are constrained to use only FCC-allowed RF heating frequencies which are quite broadly spaced. Currently, 13.56 MHz operation appears suitable for ICP sources capable of 200 mm diameter wafer processing (see section 5).

4. Plasma characteristics

Ion and electron density, electron temperature and plasma potential with respect to ground can all be readily measured with a Langmuir probe, although at RF frequencies care must be taken to allow the probe to follow the RF fluctuation of the plasma potential [34]. The literature gives several examples of such measurements in ICPs which show ion densities in excess of 10^{12} cm^{-3}. Immersed-coupler, pulsed RF ion sources [26] achieve up to 6×10^{12} cm^{-3} in He at 1–5 mTorr with up to 100 kW pulses at 1% duty cycle and 10 Hz repetition rate. The discharge is surrounded by a magnetic bucket which gives 10% uniformity over a 30 cm diameter ion extraction surface. Electron temperatures in such a plasma are in the range of 2–7 eV. Ion temperatures at 0.4 mTorr are reported to be as high as 0.8 eV as measured by Doppler line broadening of argon under high-power (55 kW) conditions. This phenomenon is attributed to RF power coupling to the ions. Ion heating is not surprising since the excitation frequency (1 MHz) is much less than the ion plasma frequency ($\omega_{pi} \simeq 100$ MHz).

Amorim *et al* [6] report electron temperature in a 3.8 cm diameter helical ICP of 10 eV and an ion density in the mid-10^{12} cm^{-3} range at 64–130 mTorr with only 370 W of absorbed RF (11.4 MHz) power (see figure 6). The higher electron temperature is likely to have been caused by increased diffusion losses due to the small diameter of the discharge vessel and absence of magnetic confinement. The plasma density versus power in figure 6 shows discontinuous transition from a low-density mode where $n_i < 10^{11}$ cm^{-3} to a high-density mode where $n_i > 10^{12}$ cm^{-3}. The authors attribute this phenomenon, which they observe above 30 mTorr, to a transition from a low density E-discharge to a high-density ICP (H-discharge). The discharge is easily excited in this plasma

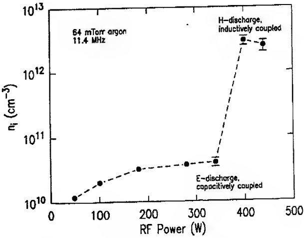

Figure 6. Ion density versus power in a helical ICP increases abruptly as the coupling mode changes from capacitive to inductive. At pressures below 30 mTorr the transition is continuous (after [6]).

source since no split Faraday shield (see figure 1(*a*)) was used to eliminate capacitive coupling.

In the ICP shown in figure 1(*c*) with a chamber width of 27 cm, the electron temperatures vary between 3 and 8 eV for pressures of 30–0.3 mTorr respectively [35]. As one might expect, electron temperature increases with decreasing pressure. Argon ion densities are typically 10^{11}–10^{12} cm^{-3} for RF powers of 200–1200 W. Average or DC plasma potentials in argon and oxygen also increase with decreasing pressure from 10 V at 30 mTorr to approximately 25 V at 1 mTorr. Low DC plasma potentials are due in part to the multipolar magnetic confinement used in this system which slows electron diffusion losses. The RF variation of the plasma potential has also been measured using a calibrated capacitive probe. For RF powers above 500 W the RF potential variation in the plasma is typically less than 10 V_{rms} and is dominated by the fundamental frequency with little harmonic content. Low plasma potentials are important to low-contamination plasma processing since ions accelerated from the plasma to the chamber walls by high plasma potentials will cause sputtering of wall materials.

5. Applications of ICPs

Yamashita [25] describes an immersed ICP sputtering apparatus which obtains densities of 10^{12} cm^{-3} in argon. The metal target is DC-biased at one end of the helical coil and the substrate is placed facing the target at the opposite end. In this deposition configuration the sputtered material can be ionized as it passes through the inductively coupled discharge. It is estimated that the ionization fraction of sputtered material at the substrate is as high as 65%. Metal deposition rates are also reported for Al (4250 Å min^{-1}), Ti (2200 Å min^{-1}), Fe (4400 Å min^{-1}), and Cu (11 200 Å min^{-1}) in 10 mTorr argon with 700 W RF power and 800 W DC sputter target power.

Ho and Sugano [36] have used an ICP for selective anodic oxidation of silicon. Substrates were positively biased (typically +30 V) and heated to 600 °C in a 0.2 Torr oxygen plasma generated by 1 kW RF power at 420 kHz. Oxygen ion density was reported at 1×10^{12} cm^{-3} and oxide growth rates of $>0.8\,\mu m\ h^{-1}$ were achieved. The measured interface-state density after annealing was comparable to thermal oxides, which attests to low contaminant levels.

Large-area plasma processing has been demonstrated in a planar, spiral inductor ICP [37]. Polyimide coated on glass substrates has been etched at 3800 Å min^{-1} in 5 mTorr oxygen with 500 W RF power. No external bias was applied to the substrate, but ion impact energies are estimated to be ≃10–15 eV from the difference of the plasma potential and the floating potential V_p–V_f. The substrates were not cooled, but the process time was only 1 min and the relatively massive glass substrates were not hot upon removal from the plasma system. In this reactor, uniformity of better than 3.5% (standard deviation/average) can be achieved on substrates with diagonals exceeding 200 mm as shown in figure 7. The substrate-to-window separation is typically 5–10 cm, but in the high-density inductively coupled mode the skin depth of inductive fields, δ, is only of the order of 1–3 cm (figure 3). One can observe that the substrate is shielded from RF induction fields by the plasma.

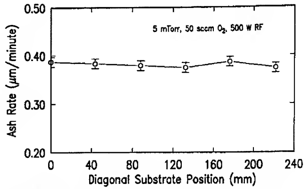

Figure 7. Polyimide ash rate uniformity of 3.5% across diagonals of greater than 20 cm is shown for the planar, spiral coupled reactor.

Radio-frequency ion thrusters [38] are an application of ICPs which date back to the 1960s. Ion beams extracted at 1–4 kV from helical ICP plasmas of Hg and Xe at (1–5) × 10^{-4} Torr are designed to provide station-keeping thrust to satellites. Ion densities of the order of 10^{11} cm^{-3} and electron temperatures of ≃1 eV are reported. Source diameters range from 15 to 45 cm. Of particular interest to ICP manufacturing concerns are proven operational lifetimes of about 10 000 hours for these gridded ion sources.

6. Summary

A brief review of inductively coupled plasma technology has identified several reactor variations. Large-area plasma can be generated using helical- and spiral-shaped inductive coupling circuit elements which are either external to or immersed in the discharge. Small-volume ICPs have also been produced by transformer coupling to a ring-shaped discharge tube with applications to lasers.

The issue of whether a particular source geometry is inductively coupled or capacitively coupled has historically been (and continues to be) a point of debate. In general, if high-density plasma generation is achieved by an inductive structure in a Faraday shielded chamber, coupling which is primarily capacitive may be ruled out. The degree of capacitive coupling impacts the contamination in the plasma from sputtering by large RF potentials between the plasma and the inductive coupling structure.

Existing models for inductively coupled processing plasmas are relatively simple from a plasma physics perspective. The primarily 'field models' treat the plasma as a conductive or dielectric medium and predict only induction field geometry and power deposition. There is

a clear need for improved models with emphasis on detailed plasma physics. There also exists a need for further plasma diagnostics of low-pressure ICPs. Since high ion density generation typically allows the ICP to operate such that $\omega < \omega_{pi}$, the ions cannot be considered immobile at the RF driving frequency. The effects of these ion oscillations on ion and neutral temperatures as well as the width of ion energy distributions incident on biased substrates needs to be documented. In addition, large RF potentials applied to the inductive coupling structures may cause some sputtering of the adjacent dielectric vacuum vessel. It is important to determine the impact of sputtering on the plasma process and, if necessary, take measures, such as split or spoked Faraday shielding, to eliminate it.

The high ion densities produced by ICPs ($>10^{12}\,\mathrm{cm}^{-3}$) over large areas ($>20$ cm diameter) have refocused attention on RF induction for use as a method of plasma generation for plasma processing. Early process data show that high rates of etching and deposition compatible with single-wafer processing are possible using this technology. The relatively simple designs and reliance on easily obtained 13.56 MHz RF power make ICPs promising candidates for meeting the future needs of IC plasma processing.

Acknowledgments

The author wishes to thank C R Guarnieri, B Robinson and J H Keller for contributed reference material and S M Rossnagel for a critical reading of this manuscript.

References

[1] Asmussen J 1989 *J. Vac. Sci. Technol. A* 7 883 and references therein
[2] Perry A J, Vender D and Boswell R W 1991 *J. Vac. Sci. Technol.* B 9 310
[3] Chen F F 1991 *Plasma Phys. Controlled Plasma Fusion* 33 339
[4] Flamm D L 1991 *Solid State Technol.* 34 47
[5] Denneman J W 1990 *J. Phys. D: Appl. Phys.* 23 293
[6] Amorim J, Maciel H S and Sudano J P 1991 *J. Vac. Sci. Technol.* B 9 362
[7] MacKinnon K A 1929 *Phil. Mag.* 8 605
[8] Petri R, Francou J-M, Inard A and Henry D 1991 *Microelectron. Eng.* 13 459
[9] Francou J-M, Inard A and Henry D 1991 *Microelectron. Eng.* 13 425
[10] Eckert H U 1962 *J. Appl. Phys.* 33 2780
[11] Eckert H U 1974 *High Temp. Sci.* 6 99 and references therein
[12] Henriksen B B, Keefer D R and Clarkson M H 1971 *J. Appl. Phys.* 42 5460
[13] Thomson J J 1927 *Phil. Mag.* 4 1128
[14] Flamm D L and Herb G K 1989 *Plasma Etching: An Introduction* ed D M Manos and D L Flamm (Boston: Academic) p 64
[15] Flamm D L, Ibbotson D E and Johnson W L 1990 *US Patent* 4 918 031
[16] Steinberg G N and Reinberg A R 1983 *US Patent* 4 368 092
[17] Gabriel F C 1975 *US Patent* 3 873 884
[18] Prototech Research Inc., Tempe, Arizona, USA
[19] Welton R F, Thomas E W, Feeney R K and Moran T F 1991 *Meas. Sci. Technol.* 2 242
[20] Keller J 1989 *39th Gaseous Electronics Conf.* (unpublished)
[21] Ogle J S 1990 *US Patent* 4 948 458
[22] Davis M H, Proudfoot G and Bayliss K H 1990 *UK Patent Application* GB 2 231 197 A July 11 1990
[23] Mukkavilli S, Pasco R W, Farooq M S and Griffin M J 1990 *Proc. 40th Electronic Components and Technology Conf. (Las Vegas, Nevada, USA 20–23 May 1990)* (Piscataway, NJ: IEEE Electronics Industry Association)
[24] Rossnagel S M, Schatz K, Whitehair S J, Guarnieri C R, Ruzic D N and Cuomo J J 1991 *J. Vac. Sci. Technol.* A 9 702.
[25] Yamashita M 1989 *J. Vac. Sci. Technol.* B 7 151
[26] Christensen T C and Guiragossian Z G T 1981 *IEEE Trans. Nucl. Sci.* 28 2666
[27] Vella M C, Ehlers K W, Kippenhan K, Pincosy P A and Pyle R V 1985 *J. Vac. Sci. Technol.* A 3 1218
[28] Quon B H, DiVergilio W F, Gekelman W, Guiragossian Z G T and Stenzel R L 1981 *J. Appl. Phys.* 52 5414
[29] Zarowin C B and Williams C K 1967 *Appl. Phys. Lett.* 11 48
[30] Bell W E 1965 *Appl. Phys. Lett* 7 190
[31] Goldsborough J P, Hodges E B and Bell W E 1966 *Appl. Phys. Lett.* 8 137
[32] Hopwood J, Guarnieri C R, Whitehair S J and Cuomo J J 1992 *J. Vac. Sci. Technol.* A submitted
[33] Cohen S A 1989 *Plasma Etching: An Introduction* ed D M Manos and D L Flamm (Boston: Academic) pp 213*ff*
[34] Godyak V A and Piejak R B 1990 *Phys. Rev. Lett.* 65 996
[35] Hopwood J, Guarnieri C R, Whitehair S J and Cuomo J J 1992 *J. Vac. Sci. Technol.* A submitted
[36] Ho V C and Sugano T 1980 *IEEE Trans. Electron Devices* 27 1436
[37] Guarnieri C R, Hopwood J, Whitehair S J and Cuomo J J 1991 *38th National Symp. of the American Vacuum Society (Seattle, WA, 11–15 November 1991)* (unpublished)
[38] Groh K H and Loebt H W 1991 *J. Propulsion* 7 573 and references therein